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STUDY OF THE ATTITUDE CONTROL HANDLING QUALITIES OF THE LEM DURING THE FINAL APPROACH TO LUNAR LANDING

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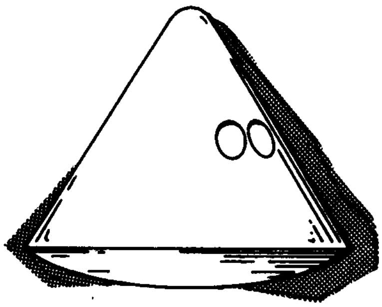

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston, Texas
May 10, 1963

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June 26, 1963

Maxime A. Faget
Assistant Director

Page 1 of 1 Page
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NASA PROJECT APOLLO WORKING PAPER NO. 1074

STUDY OF THE ATTITUDE CONTROL HANDLING QUALITIES OF THE LEM DURING THE FINAL APPROACH TO LUNAR LANDING

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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STUDY OF THE ATTITUDE CONTROL HANDLING QUALITIES OF THE LEM DURING THE FINAL APPROACH TO LUNAR LANDING

SUMMARY

A simulation study has been performed in which the handling qualities of a LEM type spacecraft have been evaluated for a lunar landing approach. Both rate command systems and attitude command systems were investigated.

The study included variations in the characteristic parameters of the control system such as thruster size, time constant, damping ratio, natural frequency and controller-command sensitivity. The effect of these parameter variations upon pilot rating of the control system has been evaluated. The study included consideration of the disturbing torques that would be associated with a misalinement of the main-engine thrust with the spacecraft center-of-gravity.

INTRODUCTION

The control system design of the Lunar Excursion Module LEM presents a difficult problem because of the varied nature of the control task during the LEM mission. The solution of this problem is made more difficult because of the large variation of mass and moments of inertia that occur during the mission. It is important then that valid knowledge of the control system requirements be applied to the design in order to insure a control system that provides satisfactory performance without undue payload penalty. A particular area of concern is the terminal part of the landing approach including hover and translation before touchdown. This portion of the maneuver is critical because the pilot must be able to select a suitable landing position (possibly where general conditions are not too suitable) and to effect a landing that will be within the design limit for the structure and which will result in a situation suitable for the subsequent launch. In other words the contact with the moon must be made under good circumstances. Although there exists considerable pilot experience with the control of vertical-landing vehicles on the earth surface the different environment of the moon, particularly the relatively low magnitude of the gravitational field, makes it difficult to extrapolate experience to lunar landing operations. Of particular concern are the handling qualities which are necessary to efficient control by the pilot. Also of concern are the techniques that are employed and the displays which are necessary for proper control. Because of the large amount of fuel which could be expended by an over-conservative approach to the lunar landing it is important that an objective analysis be made to determine procedures and control techniques which would be in keeping with desired mission success both from the standpoint of safe-reliable operations and from the standpoint of reasonable payload capabilities.

In order to provide some of the needed handling qualities information a simulation study program was initiated by the Flight Dynamics Branch of the Spacecraft Technology Division. This program included both an in-house simulation of the lunar landing problem and a contracted study of the problem. The Columbus Division of North American Aviation Inc., was responsible for the contract study which was designated contract NAS-9-519. The results of this study are reported in reference 1. The purpose of this paper is to present the results of the MSC simulation study and the relationships of the results with those reported in reference 1.

DESCRIPTION OF LUNAR LANDING SIMULATION

General

The simulation of the final portion of the approach to a lunar landing was accomplished by coupling an analog-computed solution of the equations of motion to a cockpit containing instrument displays and control actuators. The displays and controls allowed the pilot to interpret the flight of the LEM and to provide attitude control and main engine thrust control.

Displays and Controls

The instrument displays and controls utilized in the simulated LEM cockpit are shown in figure 1. The controls included a main engine throttle actuated by the pilot's left hand and a three-axis-attitude-control actuated by the pilot's right hand. The main engine throttle control was set up according to findings of reference 1 so that minimum throttle setting (without engine cutoff) was nominally equivalent to a thrust of 1300 pounds which initially gave a thrust to lunar weight ratio of .6. Maximum throttle was set to correspond to 10,000 lbs and initially gave a thrust to lunar weight ratio of about 4.7. The attitude controller is shown in more detail by the photograph of figure 2. The diagram of control motions shown in figure 3 presents the manner in which control is commanded about all three axis and the angular throws of the controller. The angular limits of the controller (±30° in pitch and roll) give approximately $\pm 1\frac{1}{8}$ inches of controller motion at the center of the controller finger-tip grip. The type of control system utilized was varied during the study and will be described later in the Test Program.

The instrument display presented the pilot with the following information:

a. Body axis orientation with respect to local geographic coordinates. Pitch and roll attitude was presented by a three-inch diameter two-axis "eight-ball".

b. Body axis angular rates

c. Altitude

d. Rate-of-change of altitude

e. Relative downrange and crossrange position of the landing site

f. Components of horizontal velocity in body axes, $\dot{x}$ and $\dot{y}$

g. Thrust to weight ratio in lunar units (that is, T/W = 1 required for hover)

h. Fuel remaining

Scale changes could be selected by the pilot for the instruments providing range, altitude and velocity information. These scale changes provided coverage of the maximum values of the quantities presented as well as a relatively sensitive presentation for the hovering task.

The displays were limited to cockpit type instrumentation and did not provide a simulated view of the lunar landscape as was utilized in the study of reference 1. The importance of this factor is difficult to assess but it is believed that the lack of an outside-the-cockpit scenery display does not invalidate the general nature of the study results.

Equations of Motion

The equations of motion were set up to determine the six-degrees-of freedom of the LEM over a flat "moon". Because the problem was contained within about 500 feet of the lunar surface the lunar gravitational field was assumed to be constant. The moments-of-inertia of the spacecraft were assumed to be constant during the portion of the flight simulated. The mass of the LEM was assumed to vary with fuel consumption. Table I presents the assumed values of mass and inertia during the study. Also included in table I are the assumed constant values of the moment arms of the reaction control thrusters and a schematic of the axis system assumed.

Attitude Control System

Three types of attitude control systems were simulated: (a) rate command, (b) attitude command and (c) open-loop or acceleration command. Only a qualitative evaluation of the open-loop system was made to indicate the difficulty of the control task with this system and the majority of the study was centered on the rate command and attitude command systems. A diagram of rate and attitude command control systems utilized are shown in figure 4. In each control system it was assumed for reasons of simplifying the study that a control thrust could be generated proportional to an error signal within the limits of the maximum thrust level assumed. It is considered probable that the reaction control thrusters of an actual lunar landing vehicle will operate in an on-off fashion. A future extension to the present study will be made to evaluate the relative significance of on-off thruster operation. Angular rate and position information were assumed to have negligible dynamics and only the attitude control stick was assumed to have dead band. The main parameters that were varied during the course of the study included:

a. Thruster size

b. Controller command sensitivity (number of deg/sec or deg commanded per degree-of-stick motion)

c. Response time constant (for rate-command system)

d. Natural frequency (for attitude-command system)

e. Damping ratio (for attitude-command system)

The combination of the latter three parameters with various limits on the size of the attitude control thrusters often led to the control system being linear over only small angular ranges.

TEST PROGRAM

The test program was flown by three test subjects. Two of the subjects were currently qualified pilots with military-flight backgrounds. The third subject was a research engineer familiar with control problem analysis but without piloting experience. Two types of task were utilized and are defined as follows:

a. Hover Task - the task of the pilot was to fly from an initial hover position at 50 feet altitude to a new hover position 100 feet away and then maintain the new hover position for up to three minutes.

b. Landing Approach Task - the task of the pilot was to complete a landing approach to a specified position. The initial conditions were altitude = 500 feet, altitude rate = 0, distance to landing = 3000 feet downrange and 1000 feet crossrange.

In addition to flying the task the pilot was asked to qualitatively assess the control system utilizing the Cooper Rating System which is described in table II.

The test program included runs in which it was assumed that the main-engine thrust was not alined with the center-of-gravity. Variations of up to 4 inches of misalinement were tested.

The tests were designed to examine the nature of the handling qualities of the control systems for the following:

a. Rate Command System

(1) Time constant

(2) Maximum rate command for Landing Approach Task

(3) Thruster size in presence of main-engine thrust-c.g. misalinement

b. Attitude Command System

(1) Damping ratio

(2) Stick sensitivity for Hover Task

(3) Maximum attitude command for Landing Approach Task

(4) Natural frequency of control system

(5) Thruster size in presence of main-engine thrust-c.g. misalinements.

RESULTS AND DISCUSSION

Rate Command System

General

The simulated cockpit displays and controllers were generally similar to those used in reference 1 and it was of interest to see if the lack of an outside-the-cockpit display of the terrain would alter the evaluation of handling qualities. Enough runs were made with the rate command system to allow a rough evaluation and it was found that this evaluation agreed quite well with that of reference 1 with respect to the satisfactory range of control command sensitivity. The present results show that the satisfactory control area extends to a time constant of 1.0 second compared with about 2.0 seconds in reference 1. Part of this difference could be attributed to the lack of an outside-the-cockpit display in the present study. In addition, the attitude "eight-ball" display of the present study had a lower visual resolution capability due to its smaller diameter (3 Inch for present study and 5 inch for reference 1). Figure 5 presents the evaluation for roll rate command and also shows the corresponding results of reference 1.

The present simulation did not limit the reaction thrusters to linear operation but allowed for saturated operation. The gains of the control system could therefore be adjusted to take advantage of the thruster maximum angular acceleration capabilities to obtain desired angular rates. It was apparent from the test results that the presentation of handling qualities in the manner used in figure 5 may be misleading because the implied linear-response type control system may not be optimum when the attitude-control thrusters are limited in size. It appears more applicable for a rate command system to be presented as a plot of maximum rate command as a function of "equivalent system time constant" (time to reach 63.2 percent of steady state value). Such a plot is presented in figure 6. This figure indicates that for the type controller utilized in the simulation that available control command of from about 10°/sec to about 34°/sec was satisfactory to the pilot as long as the time constant is less than 1.0 seconds. The inference is that the available rate command is the important parameter and within a satisfactory range of this parameter the pilot will tolerate time constants of up to about 1.0 seconds. The rate command sensitivity to controller deflection may be obtained by dividing the available deflection (30° angular of 1 and $\frac{1}{8}$ inches equivalent linear) into the above quoted satisfactory available control commands. The desired control sensitivity is thought to be a function of controller configuration and caution should be applied when applying the control command sensitivities of the present tests to different controller configurations. The figure also shows optimum performance lines for 100 pound and 200 pound thrusters to indicate the magnitude of rate command as a function of response time that could be approached with these thrusters.

Effect of Main Engine Thrust-cg Misalinement

The effect of the main engine thrust being misalined with the LEM center-of-gravity was found to be quite significant. Figure 7 shows the deterioration in pilot rating as the thrust misalinement is varied from 0 to 4 inches. Variations for two thruster sizes 100 lbs and 200 lbs each with system time constants of .1 and .5 sec are shown. All four control systems are satisfactory for 0" misalinements. The deterioration for the 100 lb thrusters is much more rapid than that for the 200 lb thrusters. The variation of the 100 lb thrusters shows the advantage of the lower time constant in that the rating of the $\tau = .1$ sec is about 1 and $\frac{1}{2}$ rating points better than that of the $\tau = .5$ sec with the rating system used. The 200 lb thrusters have a similar but less pronounced incremental difference in rating.

The results of the runs with the main-engine thrust misalinement indicated that the control system should have a greater margin over the disturbing torque than was originally thought necessary. As an indication of the margin that is necessary a plot of pilot rating versus the parameter describing the ratio of the control torque to the disturbing torque was made for 200 lb and 60 lb thrusters. This plot is shown in figure 8. The figure again shows the deterioration in rating as the misalinement is increased (ratio-of-control acceleration to misalinement acceleration is decreased). The plot shows that a minimum ratio of 2 is acceptable with 200 lb thrusters and a minimum ratio of about 4 is acceptable with the 60 lb thrusters.

Maximum Rate Commands Utilized

Runs were made with the maximum available rate command varied up to 50 degrees/sec for both the Hover and Landing Approach maneuvers. In some cases even higher rates were available for the Hover maneuver. During the Hover Task the maximum commanded rate was about 20 deg/sec and during the Landing Approach maneuver the maximum commanded rate was about 30 deg/sec. It was a general pilot opinion that angular rates in excess of 20 deg/sec are not required for satisfactory control of the Landing Approach.

Overall evaluation of runs indicated that if extremely precise control of the Hover maneuver is required the pilots would desire a non-linear control system having a high sensitivity for small control deflections and a decreasing sensitivity as the maximum control deflection was approached. Currently accepted lunar touchdown criteria allow lateral velocities up to about 5 feet per second and attitude errors of at least 5 degrees. Landing point accuracy criteria has not been established but errors of the order of 10 feet would not be incompatible with the attitude and velocity criteria. Unless the touchdown accuracy requirements are drastically reduced, a linear control command variation with deflection appears satisfactory.

ATTITUDE COMMAND SYSTEM

Effect of Damping Ratio

A damping ratio of .7 is considered about optimum for normal second order linear systems. Operating a flight control system in the gravitational environment of the moon could possibly result in an optimum damping ratio other than .7 however, so several runs were made with the pilot flying the hover task in which damping ratio was varied. The results of these runs are presented in figure 9 as a plot of the magnitude of the range oscillation about the hover position versus damping ratio. For a 1 inch misalinement of the main engine thrust vector there was no apparent difference in the oscillation about the hover position for damping ratios of .5, .7 and 1.0 for a 3 inch misalinement however, the magnitude of the oscillation for .7 damping ratio was considerably less than for .5 to 1.0 damping ratio.

Effect of Control Command Sensitivity

The variation of pilot rating with control command sensitivity is shown in figure 10 for system natural frequencies of from .4 radian per second to 2.25 rad/sec. The runs plotted utilized the Hover Task for the evaluation. The variations for each natural frequency indicate that the pilot preferred a controller sensitivity which would give about 50 to 60 degrees of attitude for full control deflection. The variation of pilot rating with control sensitivity was less pronounced for frequencies of 1.24 rad/sec or greater and all runs flown with these natural frequencies were rated well within the satisfactory boundary. Throughout the study the maximum attitude command was 50 degrees during landing approach and 10 degrees during hover.

Effect of Control System Natural Frequency

Figures 10 and 11 both show the effect that variations of control system natural frequency had upon pilot rating during the Hover Task. Figures 12 and 13 show the evaluation of system natural frequency during the landing approach maneuver. For the Hover Task the pilot rating indicated that the higher the natural frequency the better the rating, although it is apparent that little additional improvement would be afforded by further increases in natural frequency above 2.25 rad/sec. For the landing approach maneuver the pilot rating indicated an optimum natural frequency of about 1.75 rad/sec. The pilot comments indicated that with higher natural frequencies there was a tendency for the pilot to induce too much overshoot.

The variation of pilot rating with natural frequency may be partly explained by considering the relationship between the attitude feedback signal and the attitude command signal generated by the pilot's control stick. If the natural frequency is changed by changing the gain on the attitude feedback then the gain of the command signal must be adjusted accordingly to maintain the same attitude command sensitivity of the control stick. Thus, for a given size control thruster a reduction in natural frequency would be accompanied by a need for a proportionately larger attitude command error signal to call for full thruster output. A reduction of natural frequency then resulted in the system being relatively slow to respond to a given attitude command.

Effect of Main Engine Thrust-Center-Of-Gravity Misalinement

Figures 11, 12 and 13 show that misalinements of the main engine thrust with the center-of-gravity is detrimental to the attitude command system as well as the rate command system. Figure 12 shows that with a thruster size of 200 lbs and a system natural frequency of 1.75 rad/sec thrust-c.g. misalinements up to 4 inches did not change the pilot rating. Increases and decreases in natural frequency however, resulted in there being a pronounced deterioration in rating with increase in misalinement. Figure 13 shows that with reduced thruster size (100 lbs) the effect of misalinement was obvious for all natural frequencies although again the preference is for a natural frequency of about 1.75 rad/sec.

Figure 14 shows the variation of pilot rating with the variation of the ratio of the available control torque and the disturbing torque due to thrust misalinement. The figure is applicable to the hover task and curves representing 200 lb and 60 lb thrusters are shown. Satisfactory control with the 200 lb thrusters is indicated whenever the ratio is about 2.5 or greater. Whereas for the 60 lb thrusters a ratio of greater than 6 is necessary for satisfactory control.

CONCLUSIONS

The simulation study of the lunar landing approach has indicated the following conclusions relative to the attitude control system.

a. The evaluation of desirable handling qualities for a rate command system was in agreement with a previous simulation study (ref. 1). A range of maximum rate command availability of from 10°/sec to 34°/sec was satisfactory.

b. Rate command system time constant should be of the order of one second or less

c. Misalinements of the main engine thrust with the center-of-gravity caused a considerable deterioration in system handling qualities.

d. The required ratio of available control torque to the torque attributed to main engine thrust misalinement varied from about 2 for large attitude thrusters (200 lb) to about 4 for small thrusters (60 lb).

e. The maximum rate that was commanded with the rate command system was 20 deg/sec during hover and 30 deg/sec during landing approach.

f. The damping ratio of the attitude-command system should be about 0.7.

g. Natural frequency of the attitude command system should be about 1.75 radian per second.

h. The attitude command system should have control thrusters capable of providing a large ratio of available control torque to main engine thrust misalinement torque. This ratio varied from 2.5 for 200 lb thrusters to 6 for 60 lb thrusters.

i. The maximum command utilized with the attitude-command system was 50 degrees during the landing approach and 10 degrees during the hover maneuver.

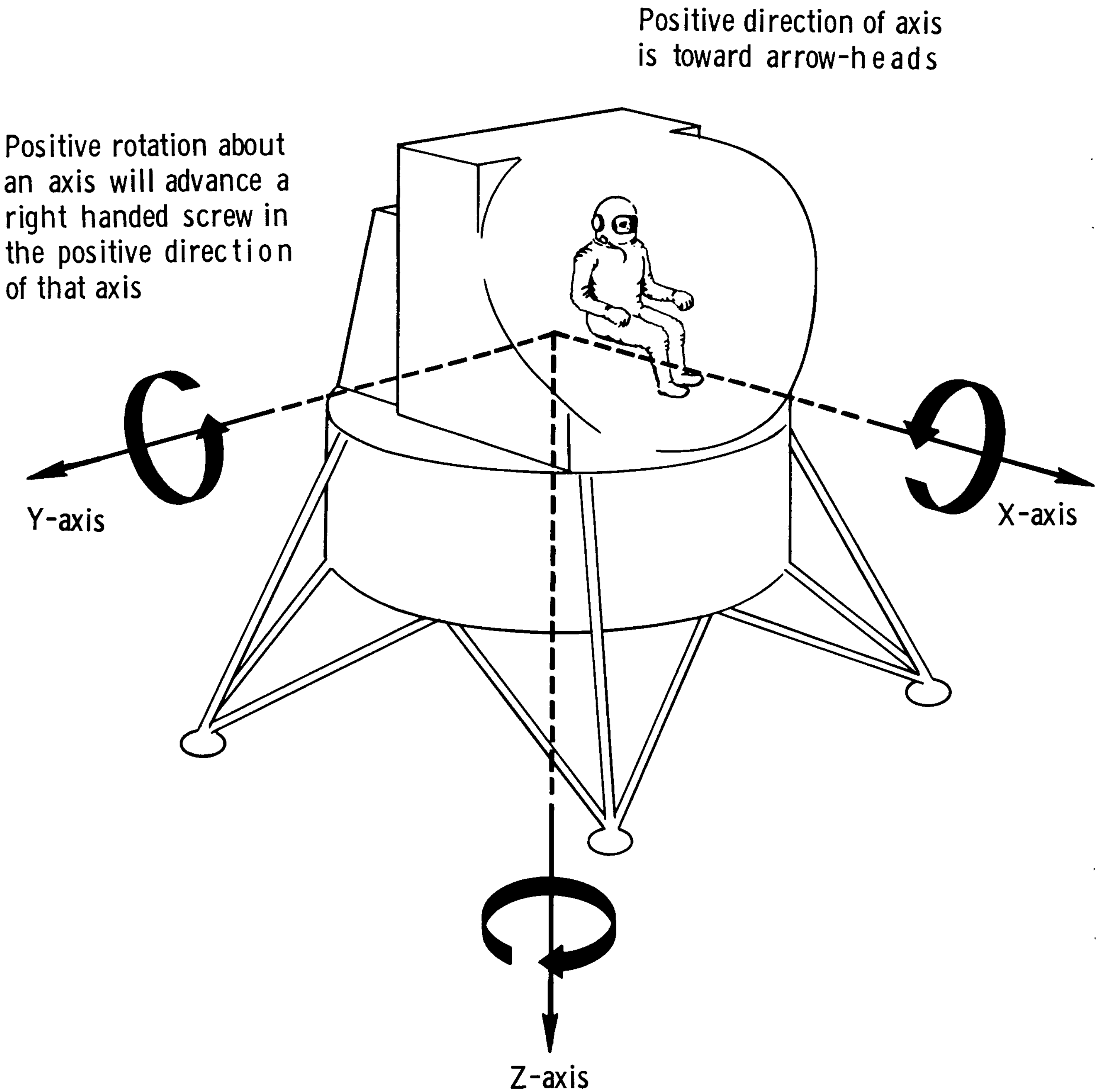
j. Control command sensitivities of the order of $1\frac{2}{3}$ degree per degree of control deflection (or 40 degrees per inch) were considered desirable.

REFERENCES

1. Hill, J. A., A Piloted Flight Simulation Study To Define The Handling Qualities Requirements For A Lunar Landing Vehicle. North American Aviation, Inc., Columbus Division, Columbus, Ohio, September 13, 1962, Report No. NA 62H-660.

Table I

Definition of LEM coordinate system



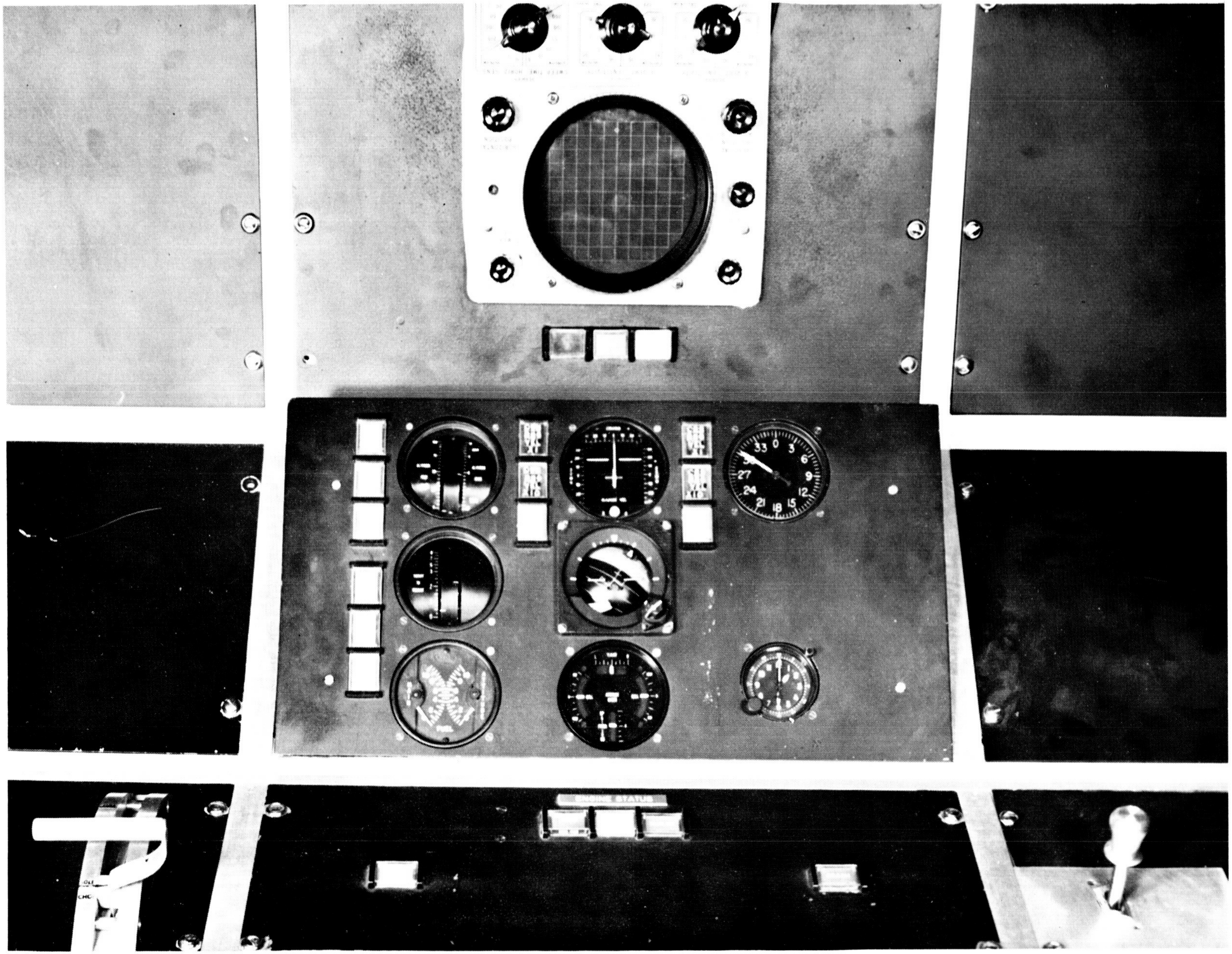
	X-axis	Y-axis	Z-axis	
Moment of inertia	6000	6000	5000	Slug-ft^2
Moment arm	6	6	5	feet

	ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED?
NORMAL OPERATION	SATISFACTORY	1	EXCELLENT, INCLUDES OPTIMUM	YES
		2	GOOD, PLEASANT TO FLY	YES
		3	SATISFACTORY, BUT WITH SOME MILDLY UNPLEASANT CHARACTERISTICS	YES
EMERGENCY OPERATION	UNSATISFACTORY	4	ACCEPTABLE, BUT WITH UNPLEASANT CHARACTERISTICS	YES
		5	UNACCEPTABLE FOR NORMAL OPERATION	DOUBTFUL
		6	ACCEPTABLE FOR EMERGENCY CONDITION ONLY*	DOUBTFUL
NO OPERATION	UNACCEPTABLE	7	UNACCEPTABLE EVEN FOR EMERGENCY CONDITION*	NO
		8	UNACCEPTABLE - DANGEROUS	NO
		9	UNACCEPTABLE - UNCONTROLLABLE	NO
	CATASTROPHIC	10	MOTIONS POSSIBLY VIOLENT ENOUGH TO PREVENT PILOT ESCAPE	

*(FAILURE OF A STABILITY AUGMENTER)

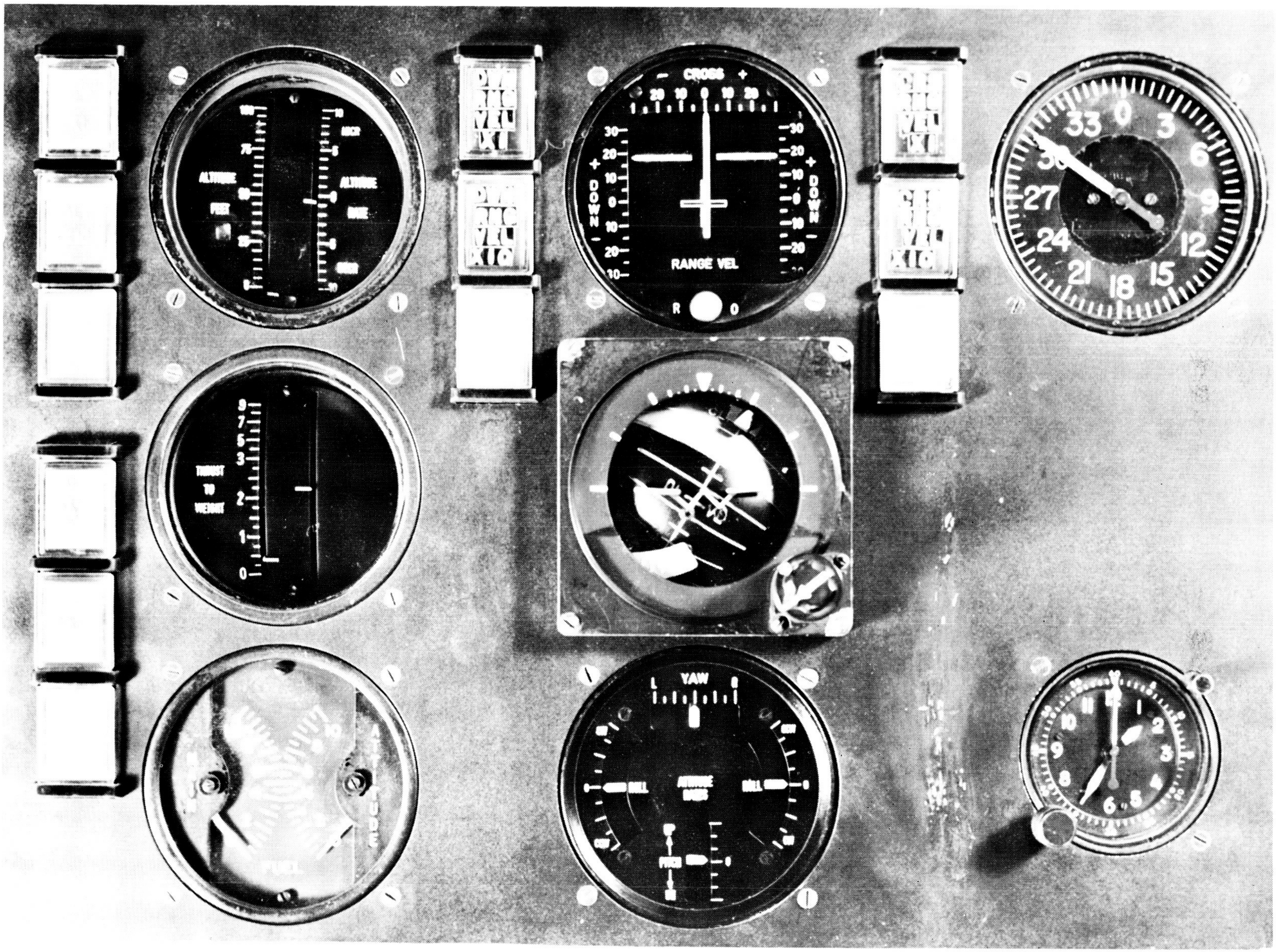
Pilot opinion rating system.

Table II



a) Instrument display and controller

Figure 1.- Photograph of simulated cockpit.



b) Close-up of instrument display

Figure 1.- Concluded.

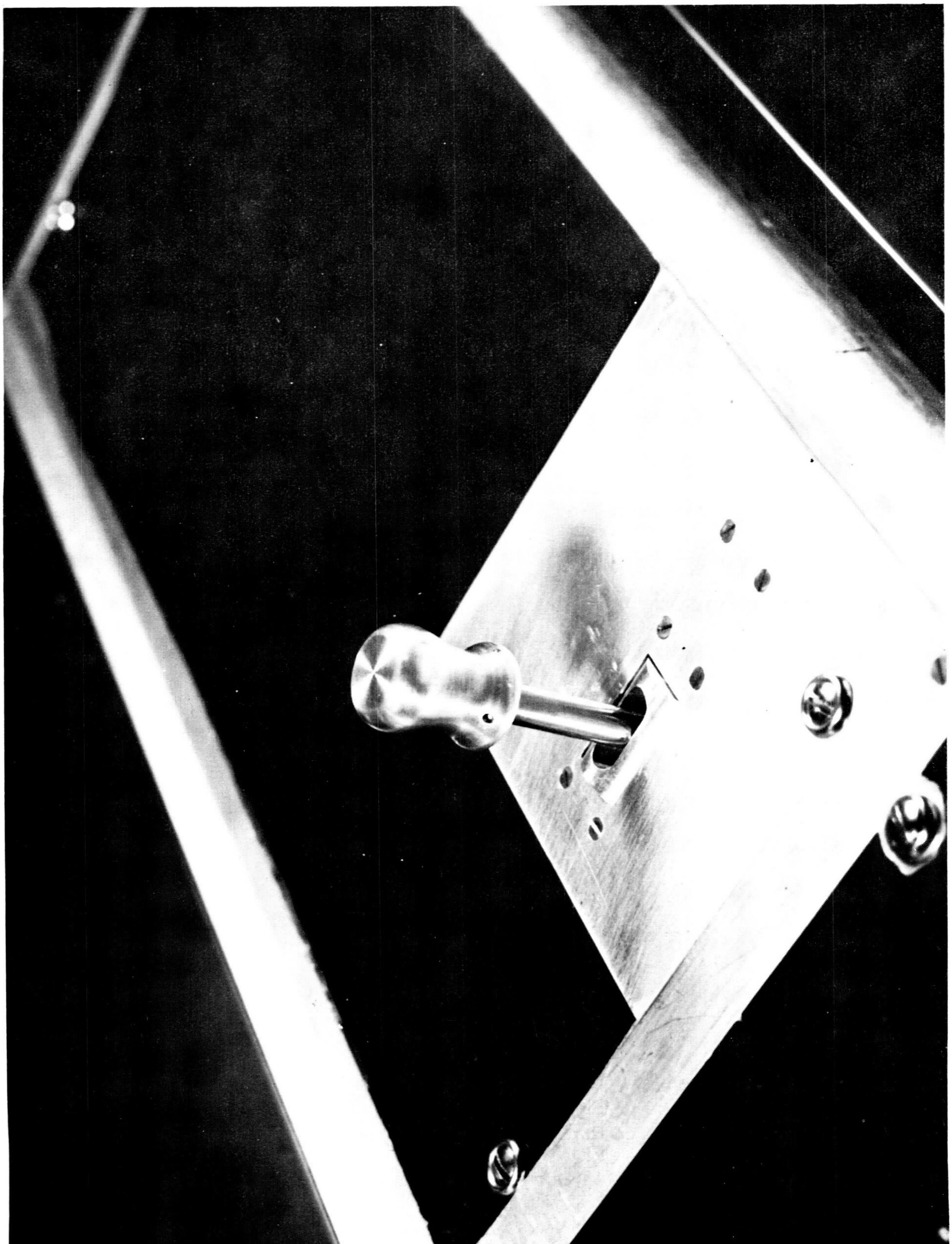


Figure 2.- Close-up of attitude controller.

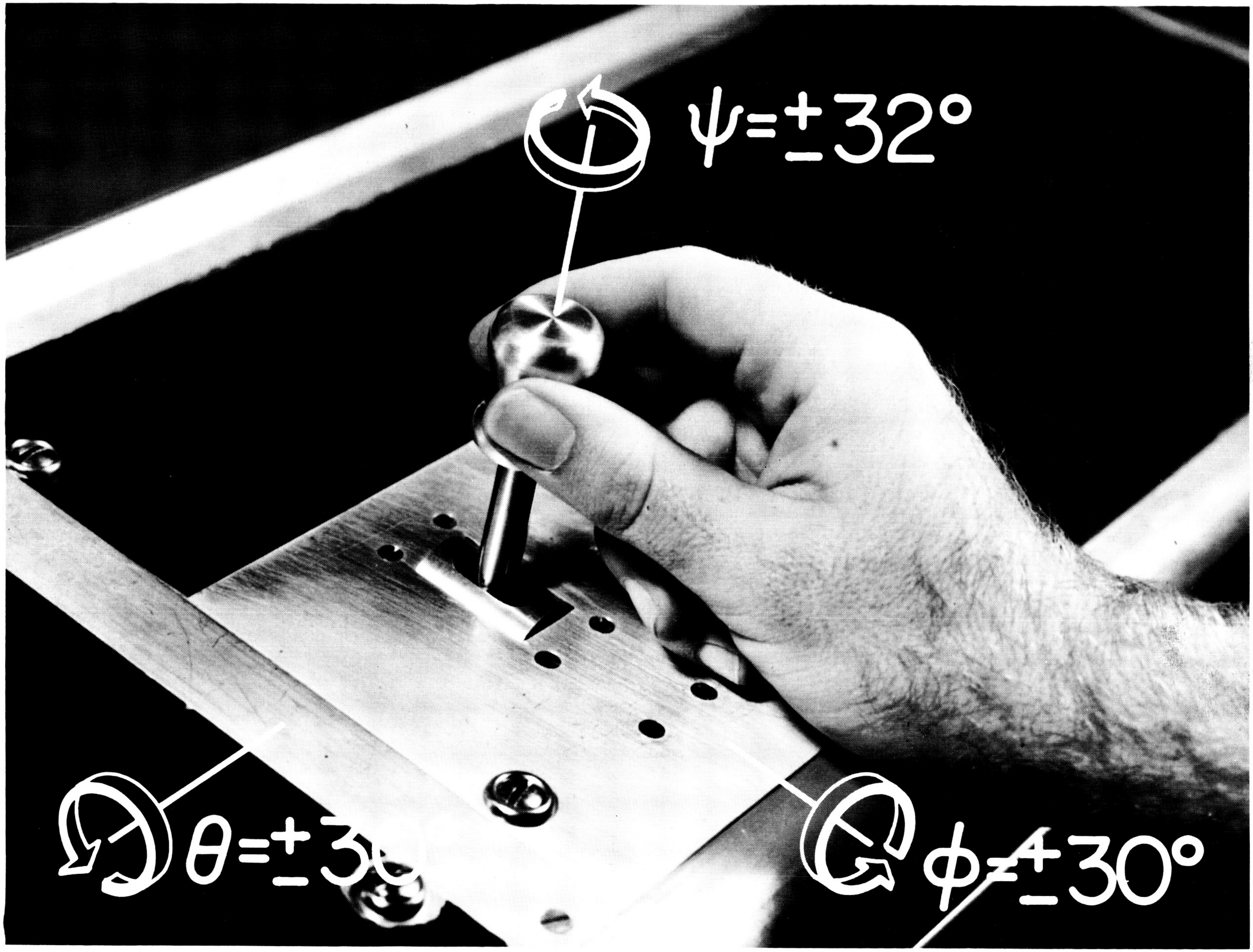
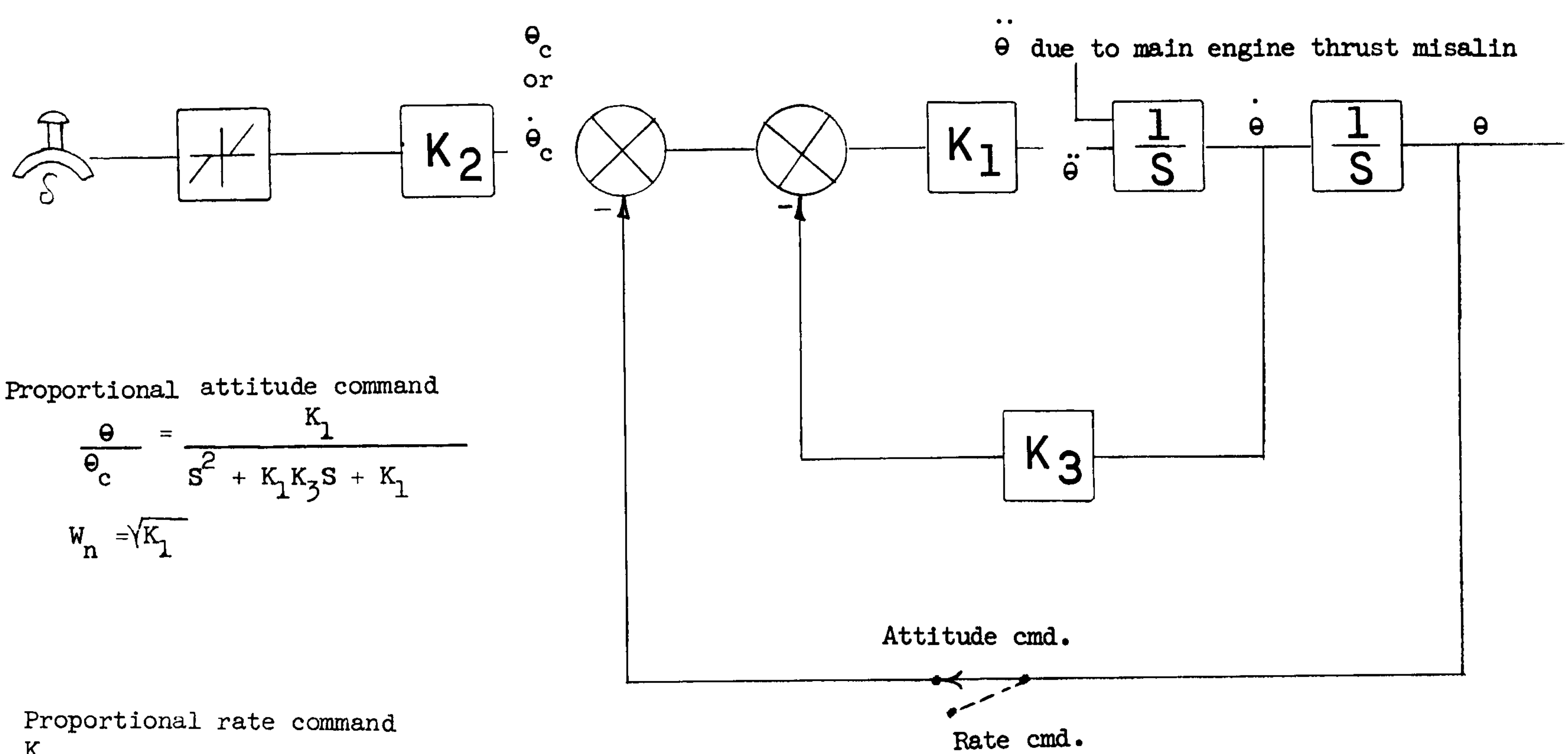


Figure 3. Hand controller motions



Proportional attitude command

$$\frac{\theta}{\theta_c} = \frac{K_1}{S^2 + K_1 K_3 S + K_1}$$

$$W_n = \sqrt{K_1}$$

Proportional rate command
K_3

$$\frac{\dot{\theta}}{\dot{\theta}_c} = \frac{K_1}{S + K_1}, \Upsilon = 1/K$$

Figure 4.- Diagram of rate command and attitude control system.

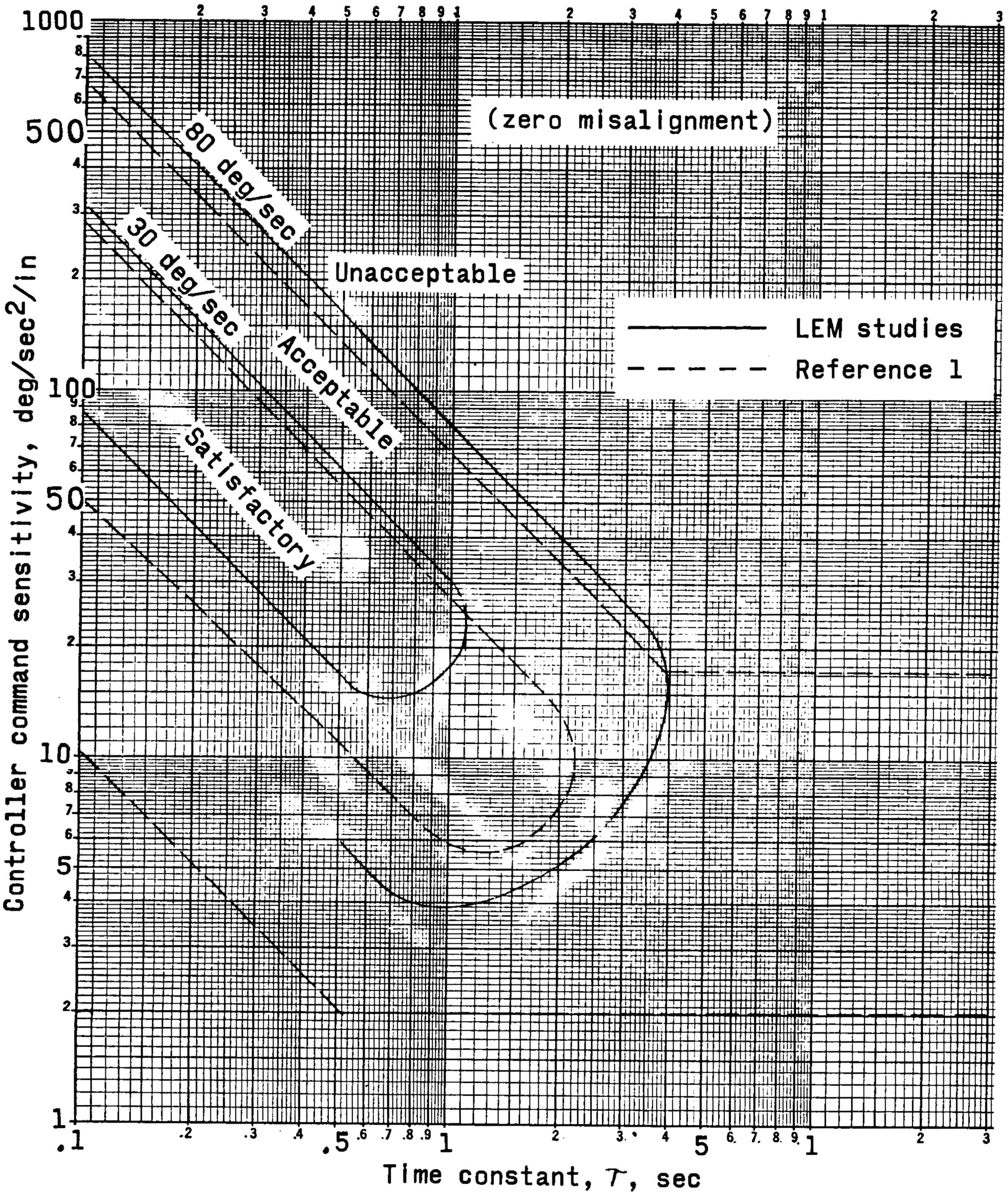


Figure 5.- Handling qualities evaluation of LEM attitude rate command for landing approach maneuver.

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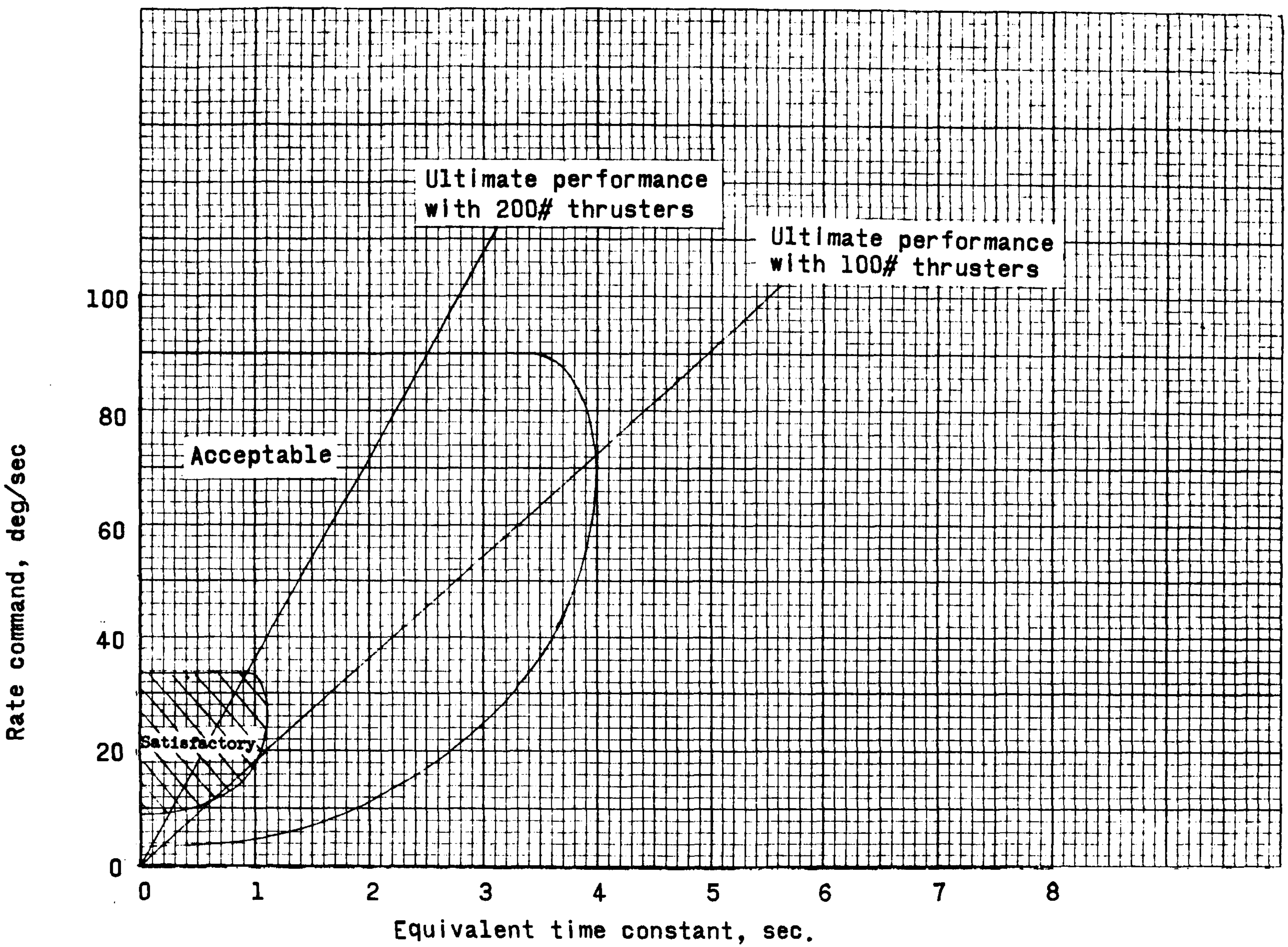

Figure 6.- Acceptance boundaries for rate command system.

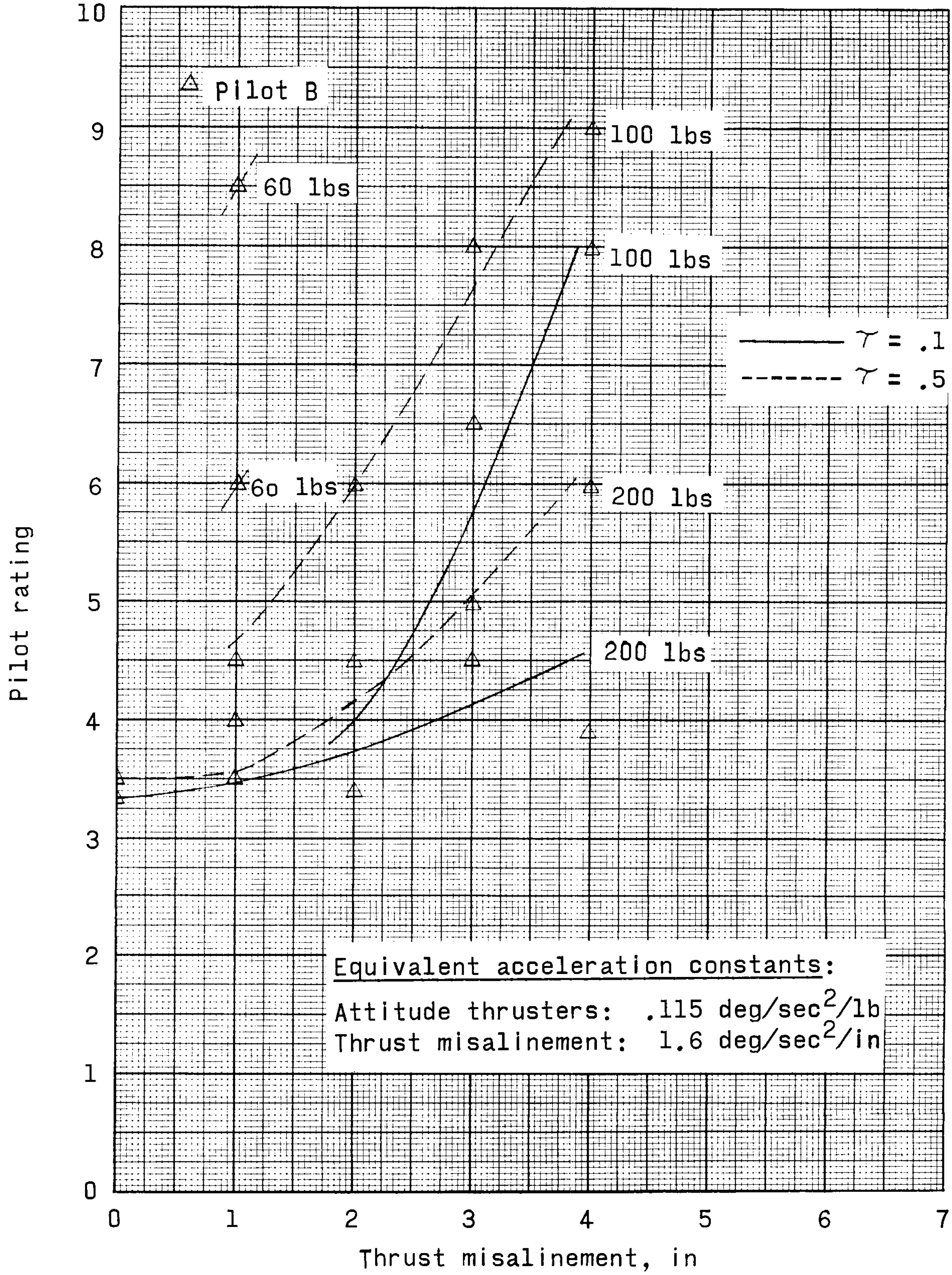

Figure 7.- Variation of pilot rating of rate command system with main engine thrust misalinement.

Landing approach maneuver

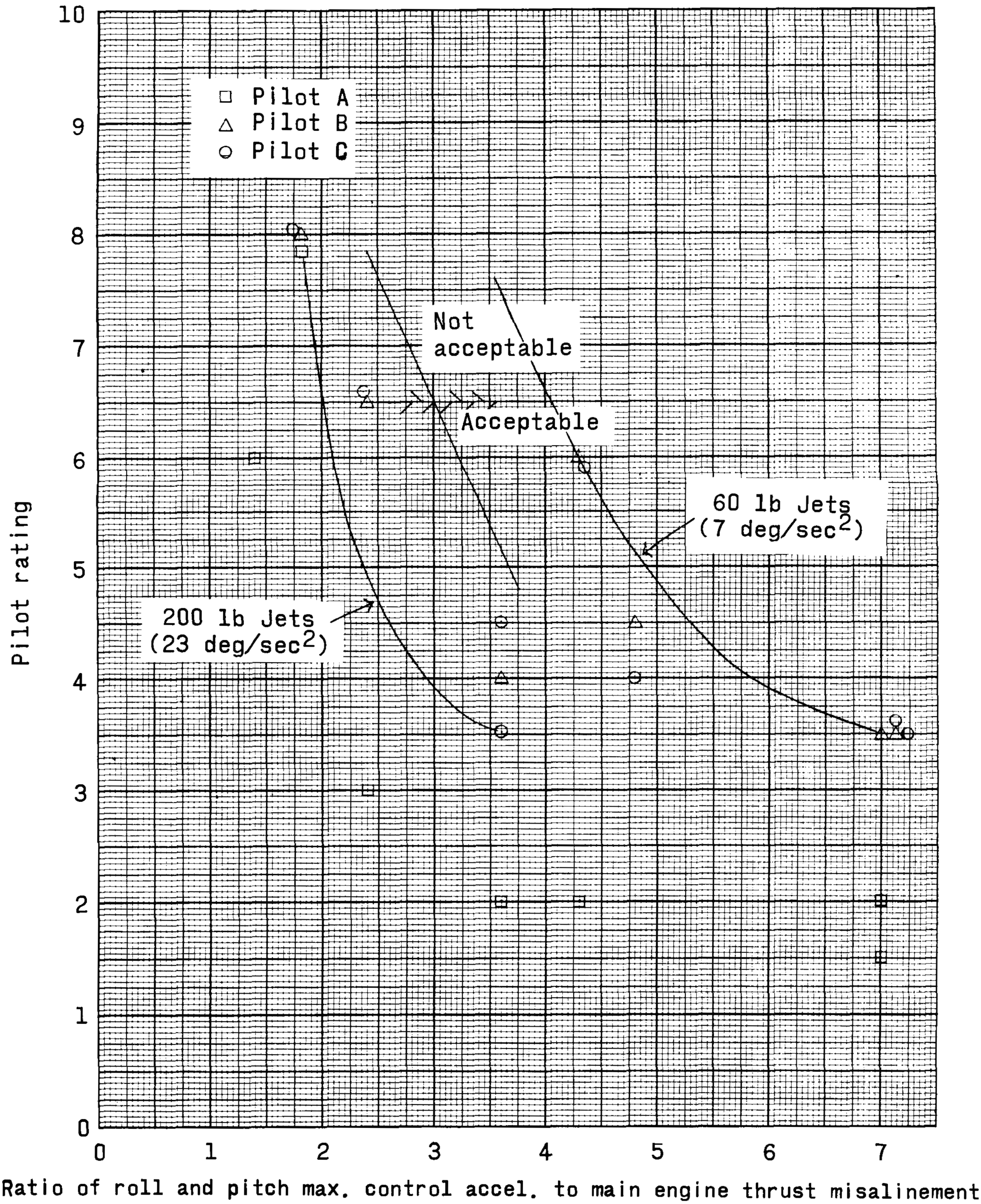

Figure 8.- Variation of pilot rating as a function of the ratio of maximum control acceleration to main engine thrust misalinement. Rate command system. Translational maneuver

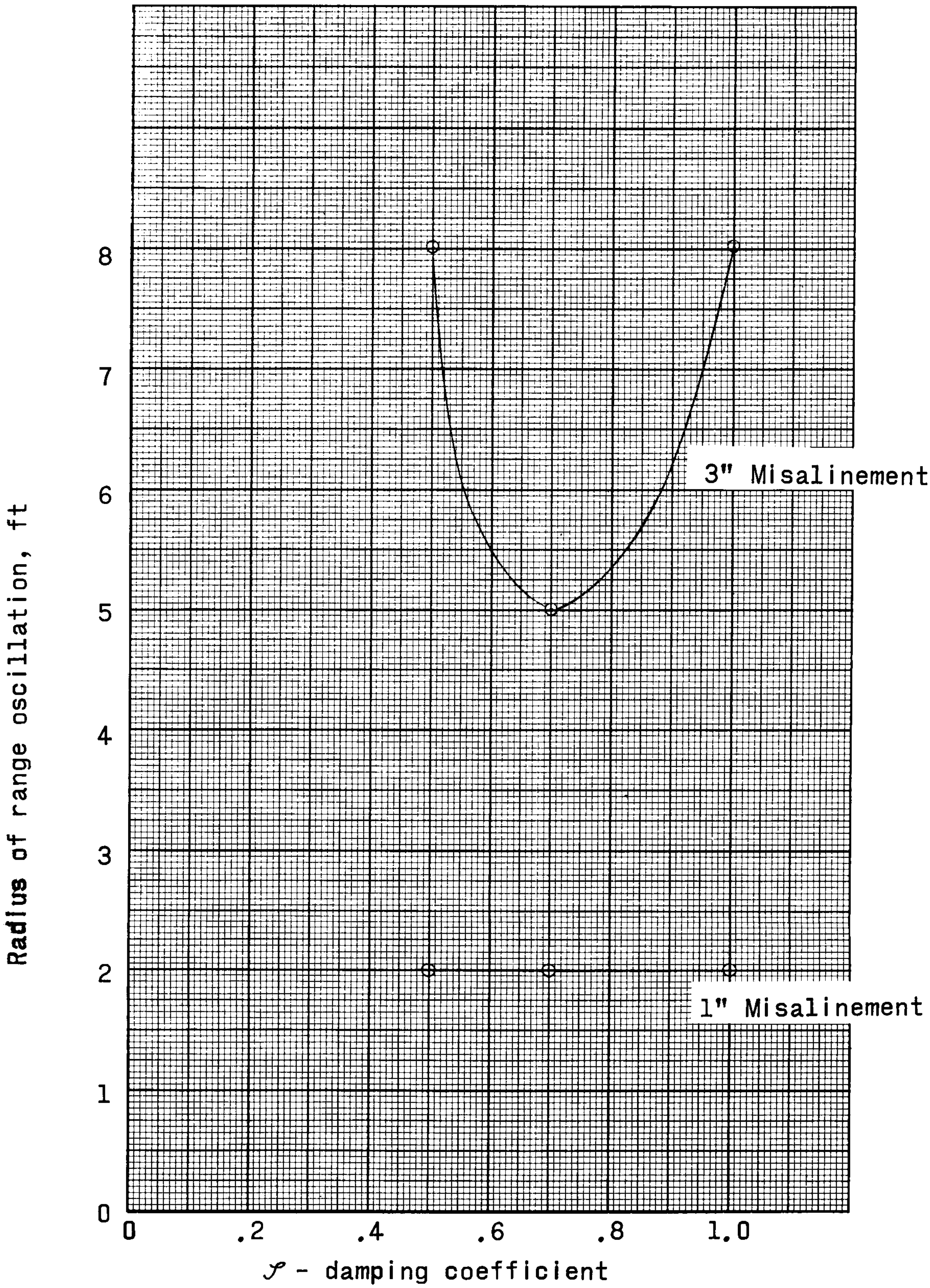

Figure 9.- Variation of pilot rating with variation of damping. Attitude command control system. (W_n=1.24 rad/sec, control sensitivity =41.6 deg/in). Hovering maneuver

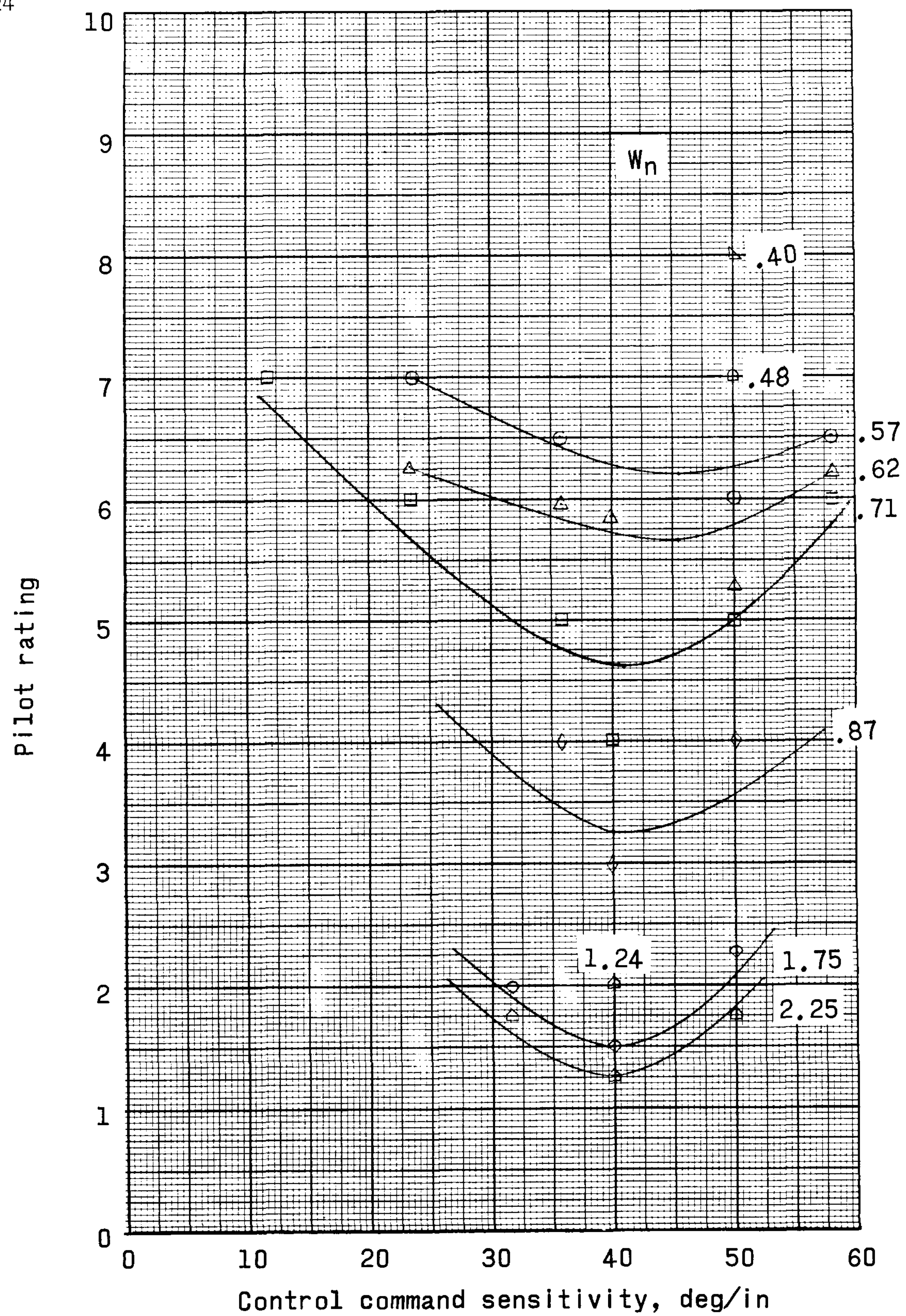

Figure 10.- Variation of pilot rating for variation of control command sensitivity. Main engine thrust misalinement = 1 in. Attitude command system. Hovering maneuver

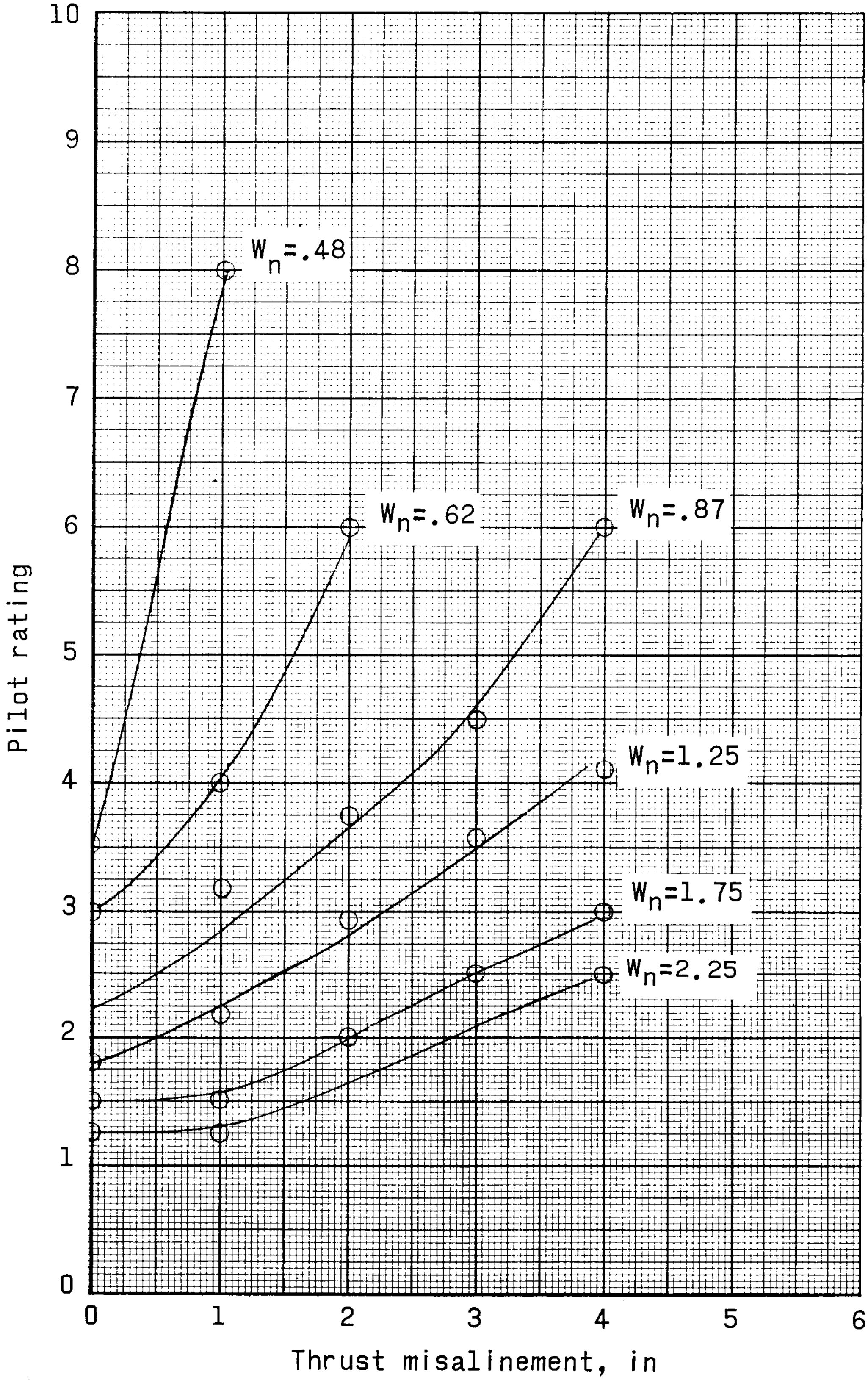

Figure 11.- Variation of pilot rating with variation of main engine thrust misalinement. Attitude command system. Hovering maneuver

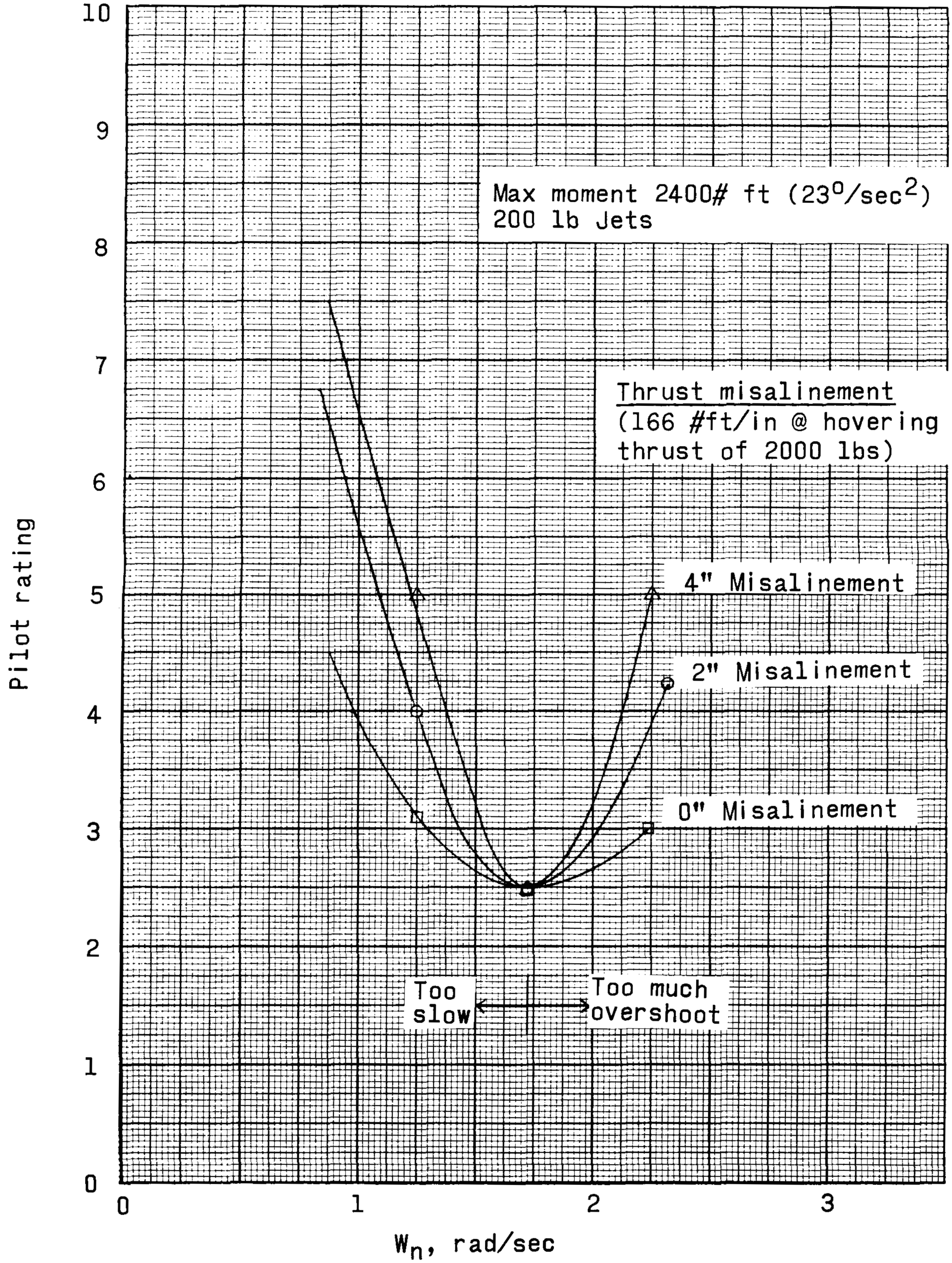

Figure 12.- Variation of pilot rating with variation of natural frequency. Control command sensitivity = 41.6 deg/in. Landing approach maneuver

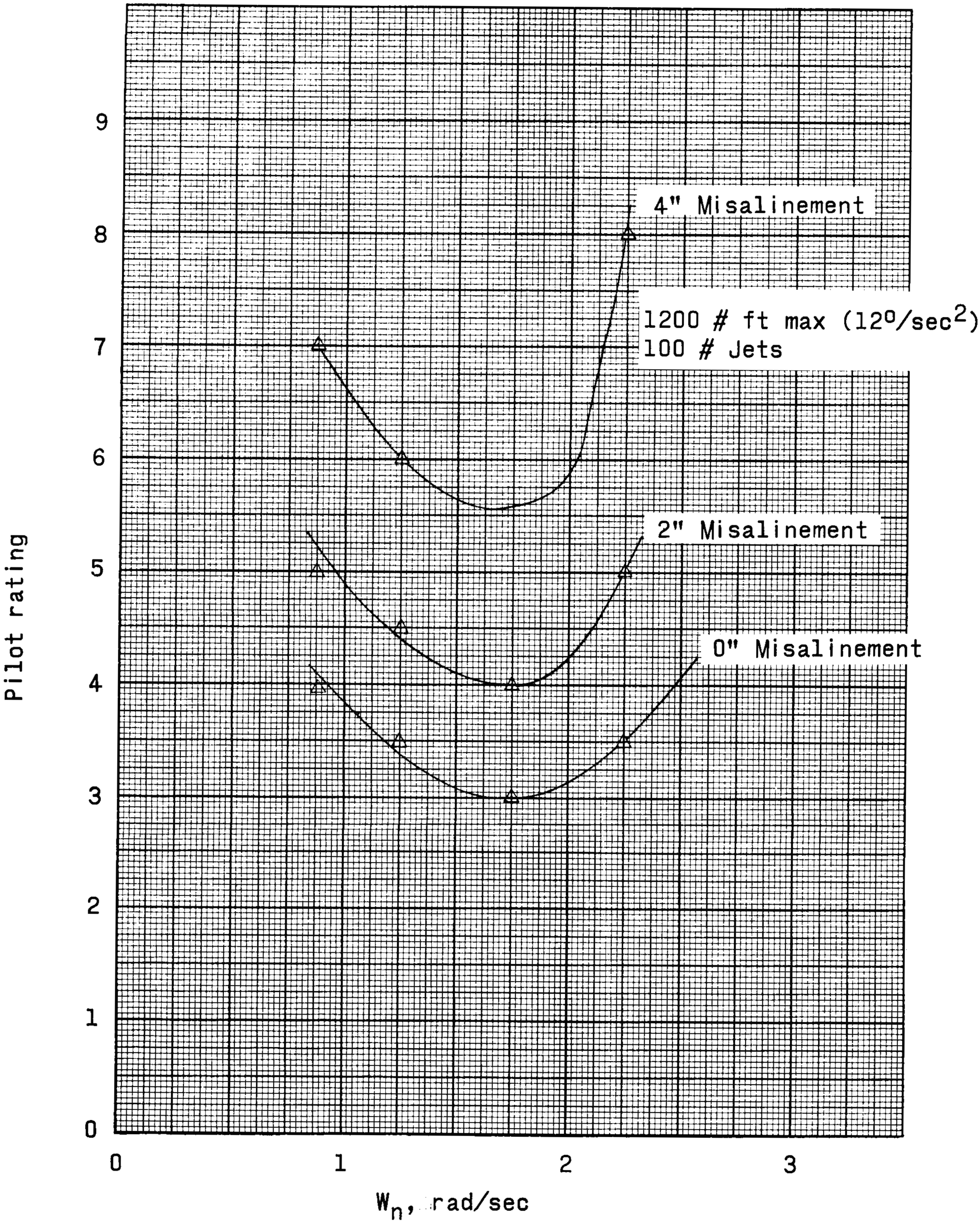

Figure 13.- Variation of pilot rating with variation of natural frequency. Attitude command system using 100 lb thrusters.
Landing approach maneuver

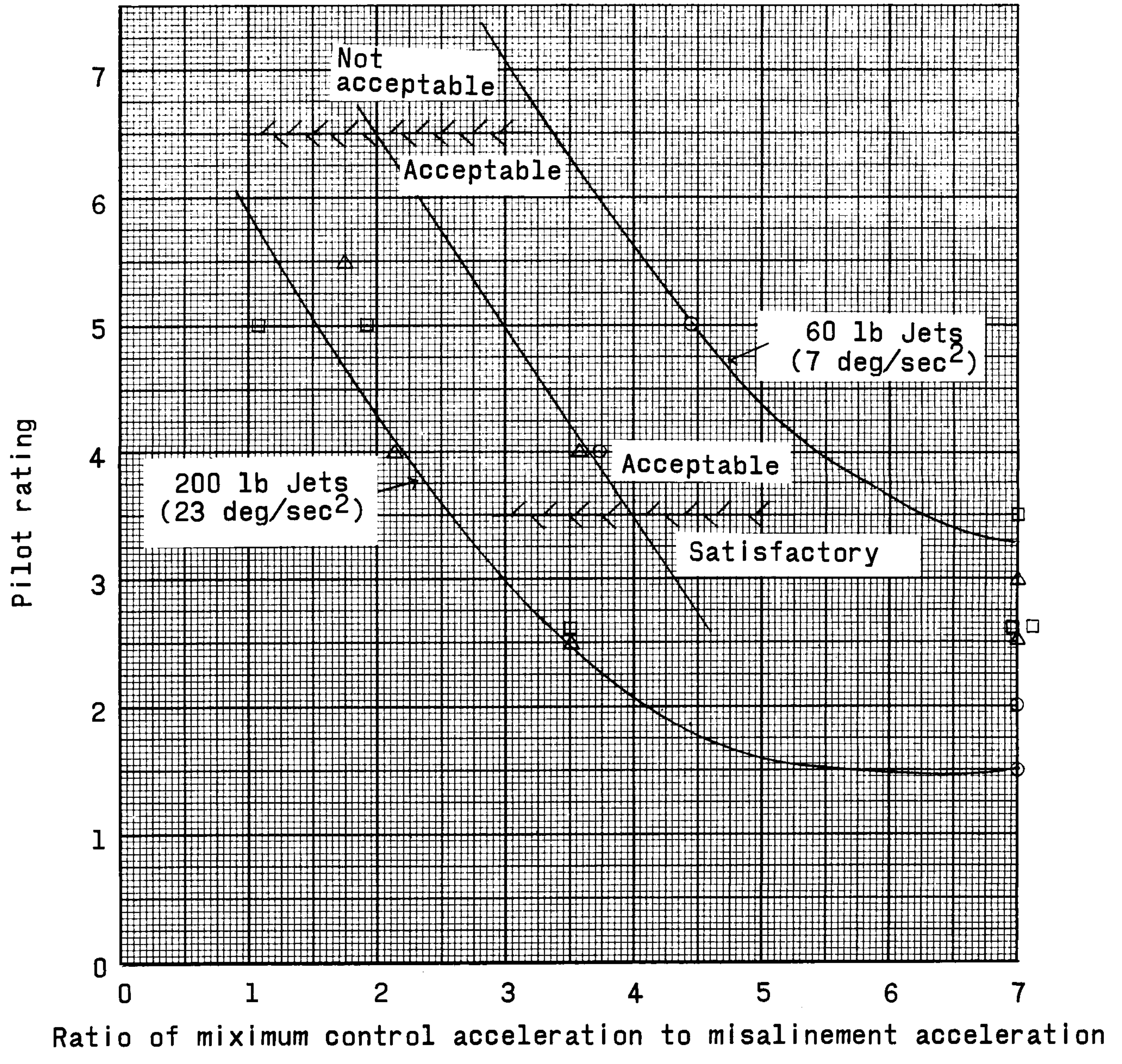

Figure 14.- Variation of pilot rating with ratios of maximum control acceleration to main engine thrust misalinement attitude command system.

Landing approach maneuver